Mechanical and hydraulic properties of the excavation damaged zone (EDZ) in the Opalinus Clay of the Mont Terri Rock Laboratory, Switzerland

Sina Hale, Xavier Ries, David Jaeggi, Philipp Blum

General comments

Research question

The current research paper addresses the question of how to easily, cost-effectively and non-destructively investigate the (time-dependent) evolution of a discrete fracture network (DFN) in an excavation damaged zone (EDZ) of an unlined lateral adit to draw conclusions for storage safety of e.g. long-term nuclear storage waste disposal. The usefulness of the proposed set of partially in-situ methods is shown by a comparison of the authors own results based on an acquired dataset in a small, unlined niche of the Mont Terri URL in Switzerland with the vast data repository from numerous scientific investigations conducted in the same overall location since 1996 (=25 years).

The authors present a four-fold dataset (measured in April 2019) consisting of:

- (43) direct measurements of hydraulic fracture aperture a_h using an air permeameter on rough fracture surfaces;
- (36) estimations of both mechanical fracture aperture a_m coupled with fracture surface roughness δa_m by the use of image analysis on a set of microscopic images on rough fracture surfaces (methodology and an automation thereof recently published by the main author);
- (47) direct measurements of needle penetration indices (NPI) perpendicular and parallel to bedding on rough fracture surfaces;
- (2) indirect measurements of the water content of an opalinus clay sample.

The set of estimated mechanical aperture a_m values and the fracture surface roughness δa_m values derived from image analysis are then related to equivalent hydraulic fracture apertures $a_{h,eq}$ via a cubic law additionally requiring single fracture transmissivities T_f measured at Mont Terri URL in other studies for plausibility purposes. The set of of NPI measurements are subsequently split into two categories (parallel and perpendicular to bedding) and a range of geomechanical and geophysical parameters calculated on a range of empirical relationships readily available in literature. Together with the determined water content of a representative sample the calculated parameters are then related to the ones available by other studies from Mont Terri data repository.

Through a classification of the investigated fractures as artificially induced unloading fractures (called "EDZ fractures"), reactivated fault planes/splays (called "tectonic fractures") and bedding-parallel desiccation/unloading cracks the directly measured and derived data is then set into context of the temporal development of the EDZ in the investigated niche and to the whole Mont Terri URL project.

Contribution of work

Presentation quality

The presentation quality of the paper is considered Excellent (1) as it is very well structured, nicely illustrated (plots and figures) and clear by not mixing its own observations with already existing and new interpretations. The abstract is of very good quality. The use of the English language is concise, does not suffer from any noticeable flaws and therefore overall makes a joyful read.

Scientific quality

The scientific quality of the current paper is assessed as Good (2) as it uses well-established approaches (i.e. air permeameter) and available data from the site as well as the vast knowledge of the Mont Terri URL site to accurately assess the performance and limitations of the authors own microimage-methodology and its applicability to similar investigations.

Overall scientific significance

The question to find an easy-to-apply methodology to characterize the time-dependent evolution of a DFN in an EDZ is interesting as well as important. The investigation of the bulk material (i.e. different facies of opalinus clay) and derived bulk chemical and physical properties as well as effective medium approximations only show the side of the story where material behavior is controlled by the bulk medium only. Although the bulk material properties may be very favorable, very local discontinuities created during excavation ("EDZ fractures") and first and foremost local to regional (re-activated) tectonic discontinuities and the transport properties along them very likely play – apart from the above mentioned bulk material considerations - a very important role in the assessment of storage safety in the host rock.

Scientific significance of the paper

The main contribution of this research lies in the comparison of the acquired dataset of hydraulic fracture apertures a_h determined by an commercial of-the-shelf air permeameter with the mechanical fracture aperture a_m coupled with fracture surface roughness δa_m determined by the image analysis approach of the first author (i.e. Hale et al., 2020b). As the conversion of geometrically measured parameters (a_m, δa_m) to hydraulic fracture apertures a_h relies on empirical relationships, plausibility of the converted values – as mentioned by the authors – rely on fracture transmissivities T_f measured by other methods (e.g. borehole geophysics) in the same overall location. Therefore, the current study as a use case for the first authors own microimage-methodology accurately depicts its main advantages (i.e. measurement range, spatial resolution) but also its own main limitation mainly due to reliance on empirical relationships as well as due to the related error propagation of large standard deviations due to variable fracture surface roughness.

If looked at from the angle of a use case of an already published methodology paper, the current research paper deserves its merit – coupled with independently acquired direct measurements of a_h or via T_f – as an incremental advance in the field of non-destructive, cost-effective, in-situ determination of hydraulic fracture parameters. The microimage-method is – as indirectly pointed out by the authors – however not a standalone method for the determination of hydraulic fracture parameters (=geometric method) that can be used independently of direct physical methods (=kinematic methods).

If the research paper is however considered as its wrapping suggests (i.e. the advancement of the understanding of EDZ in opalinus clay for long-term nuclear storage), it falls short of its aim of significantly extending the knowledge by its new dataset provided compared to the one

that is already available from the investigated site and conclusion already drawn in previous studies (i.e. knowledge of seasonal cycles, inhibition of long-term convergence, significance of discontinuity types, dependency of strength on water content, problems with low humidity environment, shotcrete application to counter dehydration etc.). The determination of NPI as an extension of the papers dataset does – in the eye of the reviewer – by itself not extend the scientific knowledge of the strength anisotropy of (altered) layered geologic media (e.g. opalinus clay) as similar methods (e.g. Schmidt hammer) have readily been used by engineering geologists and geotechnical engineers for decades.

The scientific significance of the paper is therefore assessed as Good (2) if considered as a use case for Hale et al. (2020b) but overall as Fair (3) in its current form and wrapping and in the scope of the journal Solid Earth (SE).

Summary

Although the manuscript is very well built and structured as well as very nicely and clearly presented, it unfortunately falls short by not producing an overall dataset that adds to the already vast data repository of Mont Terri URL and does by itself not offer new interpretations and conclusions that significantly add to the understanding the temporal evolution of EDZ in opalinus clay.

At the bottom line, it is therefore questionable in the eye of the reviewer if the current manuscript represents a substantial contribution to scientific progress in the scope of Solid Earth but would rather be suited to a more specific journal.

Specific comments - Questions/Issues

Positive

- Setting the scene for the significance of the overall research question in the introduction by comparing bulk rock considerations vs. different behavior of EDZs;
- Relating the later measured hydraulic fracture apertures to the main hydraulic fracture parameters;
- Establishing the chosen methods "permeameter" + "microimaging" as easy to carry out in-situ alternatives to lab methods of borehole geophysics;
- Good characterization of the study site (2.1) with detailed references;
- Suitability of air permeameter measurements for the current study with its compatibility for advective flow;
- Comprehensive and well-written description of image analysis method (Section 2.3);
- Table 1 und Table 2 for the relevant conversion of measured parameters to calculated parameters later on;
- Structural maps of the niche with data plot and KDE – very nicely illustrated!
- Figure 5: very nicely illustrated key plot of the study;
- Line 370: Clear and honest statement that direct measurement of a_h is preferable (variety of empiric relationships; error propagation etc) but microimaging offers additional geometric considerations that the hydraulic aperture does not;
- Conclusion: Fracture traces indeed offer a complementary (but not alternative) method to indirectly look at hydraulic fracture apertures;
- The "methodological trinity" indeed offers an interesting low-cost but somewhat limited approach to look at the temporal evolution of fractures in an EDZ.

Shortcomings

- Although the methodological "trinity" (i.e. air permeameter, microimaging, NPI-testing) is praised for its suitability of time-dependent monitoring of EDZ, it is however in the current study only applied at one point in time and then somehow related to the initial state after excavation. Therefore no temporal evolution is shown but only inferred by comparison to other studies;
- Schmidt hammers have been used by geologists in the industry for much longer than indicated by the authors (Line 111; oldest reference from 2007);
- Line 232: Were only nine (9) EDZ fractures measured? If yes, it is hard to make a significant statement based on a statistic comprising only nine values;
- Line 366: Related to Line 232: if only nine (9) EDZ fractures were measured, what significance does the statement have?
- Line 388ff: The data does not exhibit new findings but rather underlines existing knowledge (i.e. strength dependency on water content and fabric);
- Figure 6: although very nicely illustrated again, the addition of only one (1) dot to the compiled plots does not really underline the significance within the range of the all the data available;
- Section 3.2 does not offer a directly measured new dataset but only a calculated set of data points that does not offer room for a new interpretation. All the mentioned findings have already been reported in the (always properly referenced) literature;
- Conclusion: There is not enough data to make comparative statement of EDZ fractures (n=9!) vs. Tectonic Fractures (n=31) that would underline a statistically significant trend.

Technical Corrections

- Line 34: Is EdZ used as a synonym for EDZ?
- Line 46: Please introduce the expression THMC for the general audience;
- Line 139: EDZ fractures – is that distance measured along the niche or radial to the niche?
- Line 178: Do you mean "arithmetic mean" or "geometric mean"?